SM Higgs searches at Tevatron

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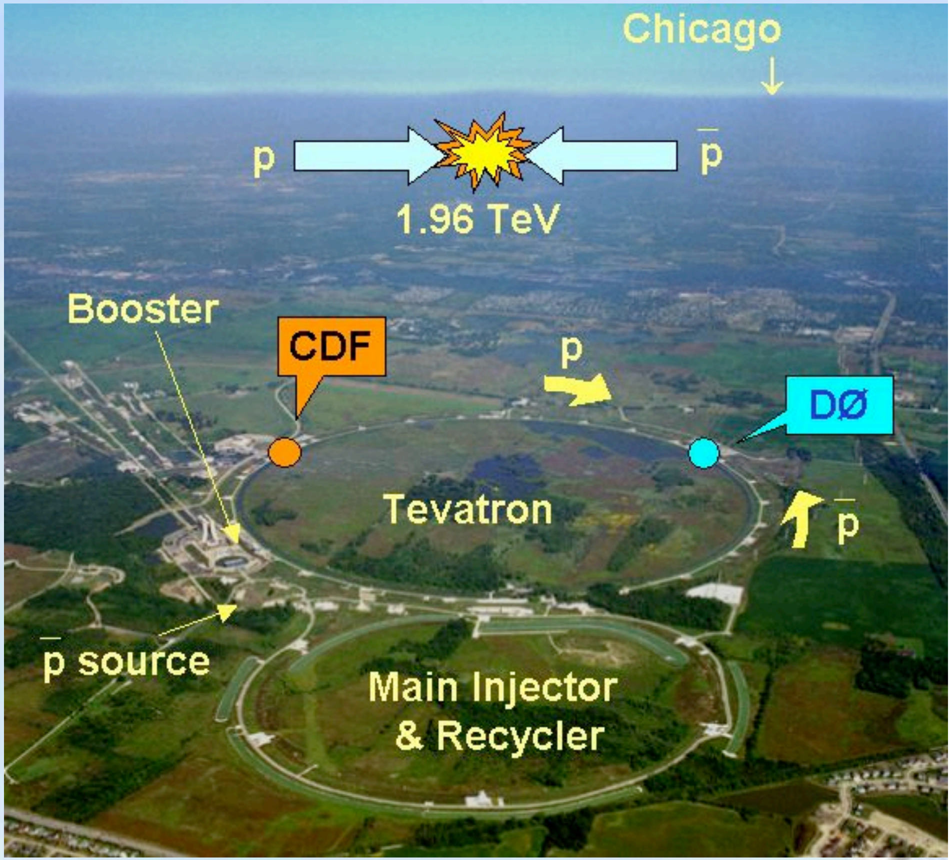
Outline

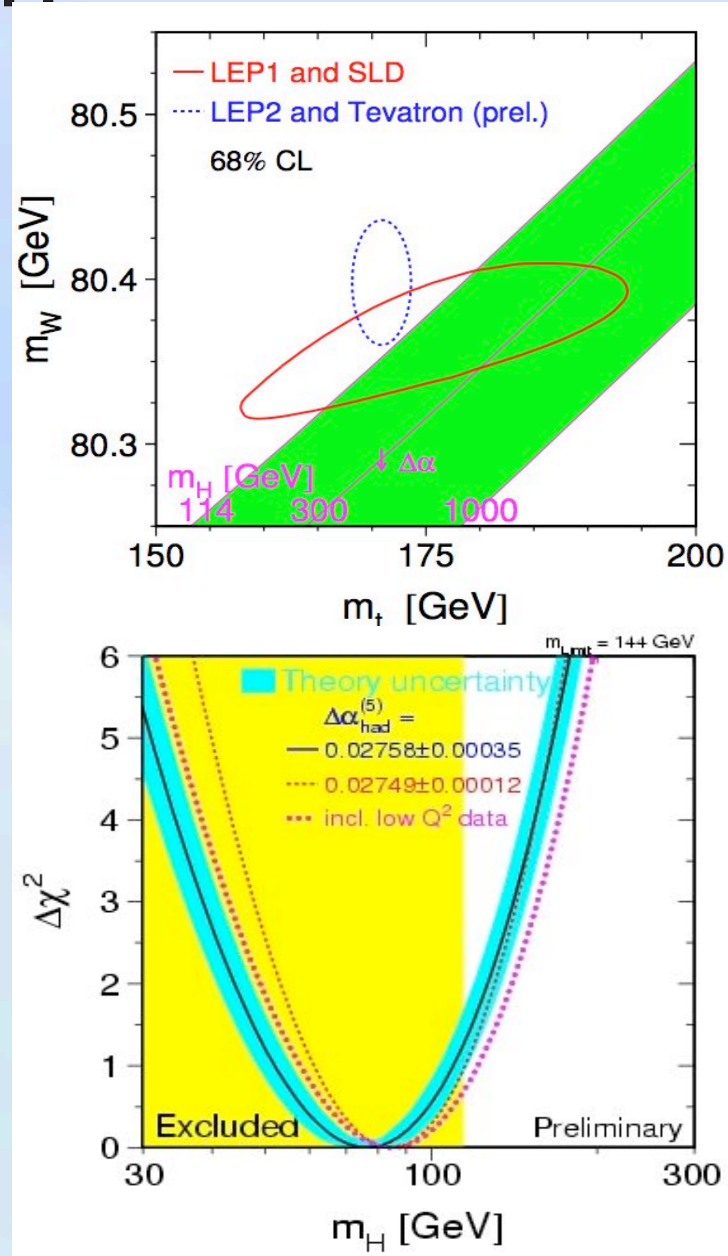
- Introduction
- Low mass SM Higgs
  - WH $\rightarrow l\nu b\bar{b}$,
  - ZH $\rightarrow l\bar{l}b\bar{b}$,
  - ZH $\rightarrow \nu\bar{\nu}b\bar{b}$,
- High Mass SM Higgs
  - H $\rightarrow W^{+}W^{-}$,
- SM Higgs combinations
- Conclusions



All results shown are done with 1 fb^{-1} of data

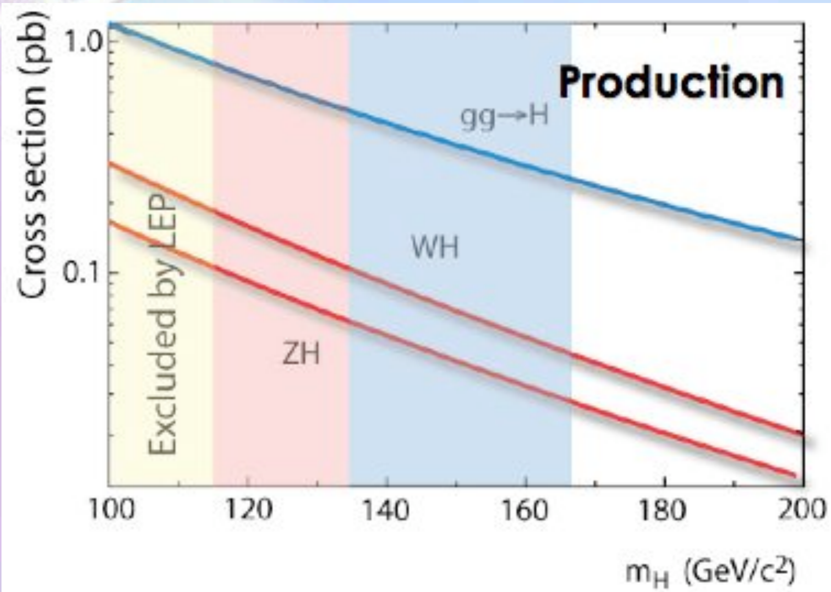
Introduction

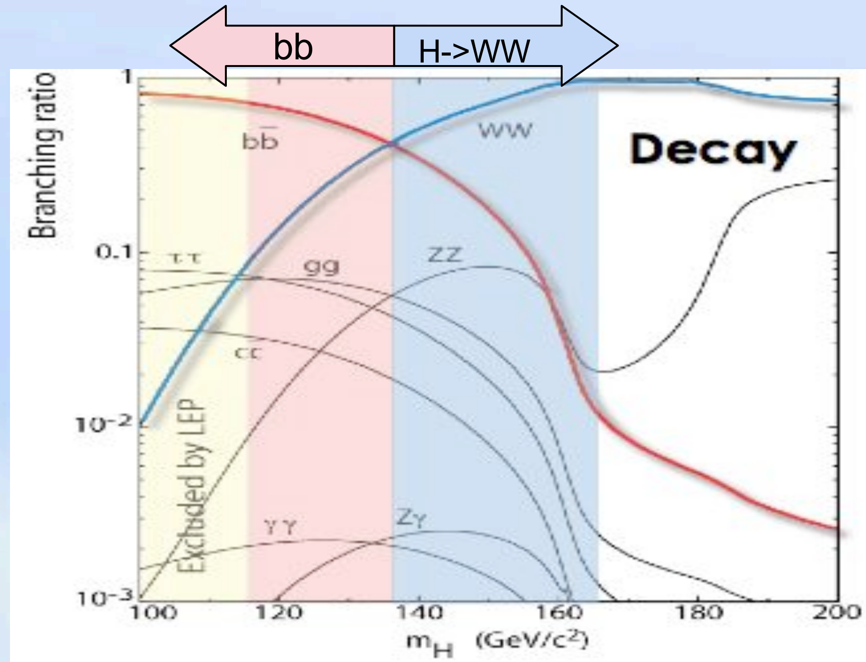
- Goal: test the simplest model of spontaneous symmetry breaking
  - One complex doublet of scalar fields resulting in a non zero VEV
  - W and Z get three of the four *d.o.f,* one left over → fundamental scalar H_{SM}
- Higgs searches has been ongoing since the 70's.
- Experimental constraints so far (LEPEWWG):
  - Direct limits from LEP2:
    - **m_H>114.4 GeV** @95%CL
  - Indirect measurements from fitting the EW data using new world average for M_{top} =170.9 ± 1.8 GeV and M_w = 80.398 ± 0.025 GeV (S. Marik and J. Wagner's talks):
    - **$m_H = 76^{+33}_{-24}$ GeV**
    - **m_H< 144 GeV** @ 95%CL (including LEP exclusion **m_H< 182 GeV)**



Data prefers low mass Higgs

SM Higgs Production and Decays





Production cross section (m_H 115-180)

- **0.8-0.2 pb range for gg->H**
- **0.2-0.03 pb range for WH**
- **0.1-0.01 pb range for ZH**

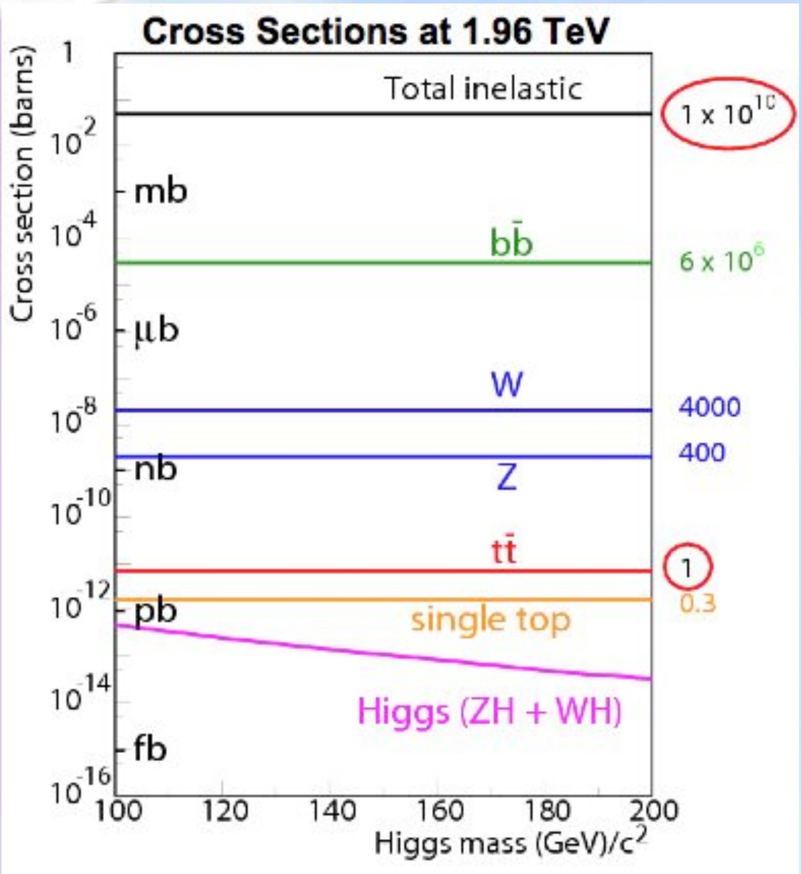
Dominant Decays

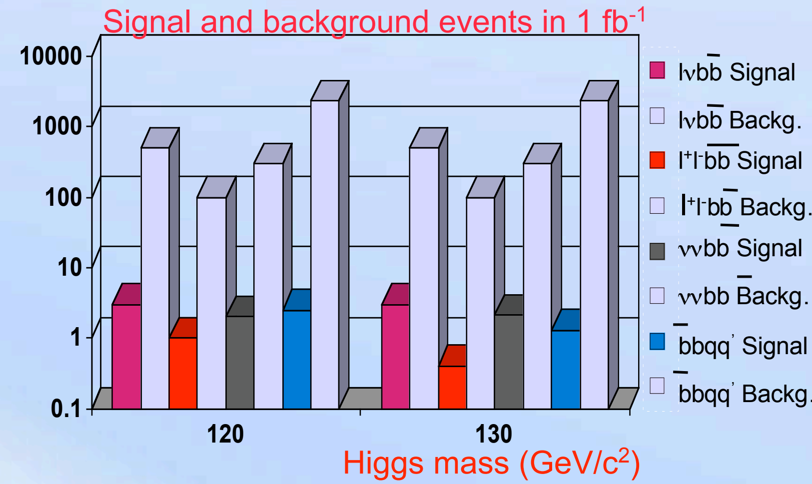
- bb for M_H < 135 GeV
- WW* for M_H > 135 GeV

Search strategy:

- M_H <135 GeV: associated production WH and ZH with H->bb decay
  - Backgrounds: top, Wbb, Zbb, dibosons…
- M_H >135 GeV: gg ->H production with decay to WW*
  - Backgrounds: WW, DY, WZ, ZZ, tt, tW

Experimental challenge at Tevatron



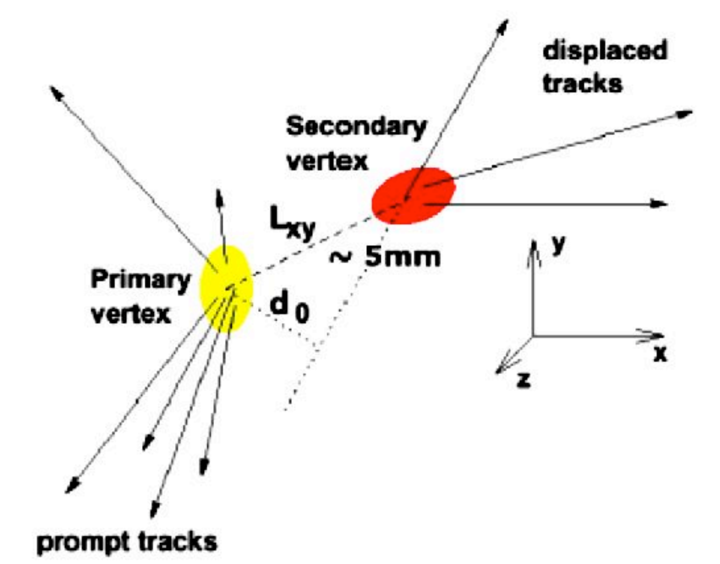


For Discovery/Exclusion, needed:

1. Improve signal acceptances:
   - Use all corners of the detectors: improve triggers, b-tagging efficiencies
2. Reduce backgrounds:
   - Improve B-tagging algorithms, dijet resolutions
3. Use sophisticated analysis techniques to extract signal from background:
   - Multivariate techniques, NN, matrix elements, etc.
4. Combine all channels, and experiments
5. Integrate as much luminosity as possible to either exclusion/discovery

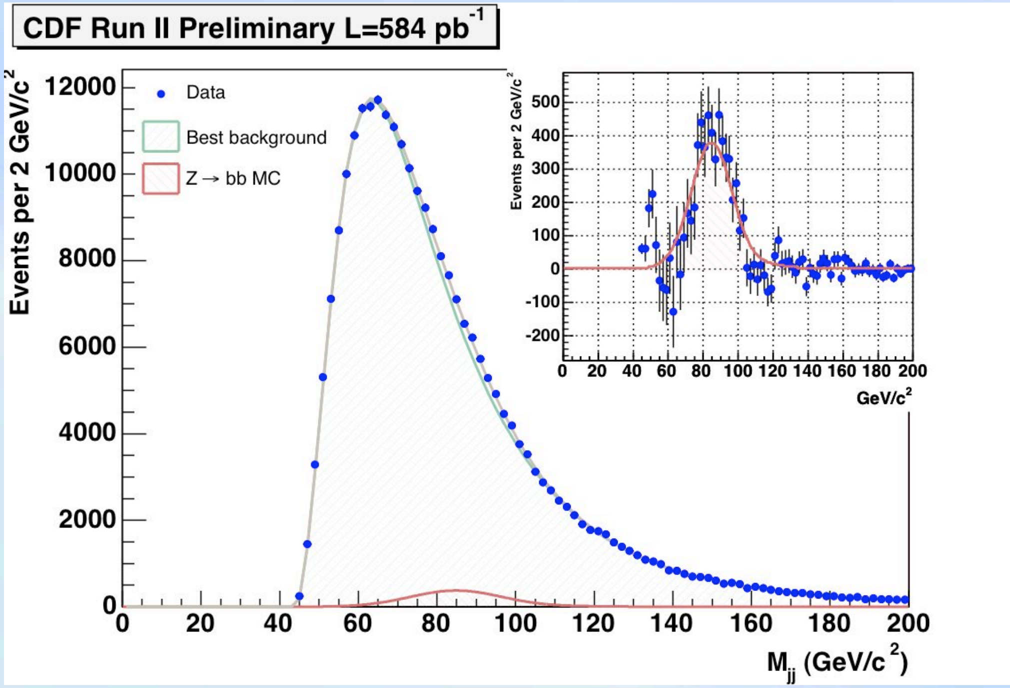
Tools to extract signal

- Improve triggers
  - Enormous effort to increase trigger acceptance for leptons
    - D0: ~100% muon acceptance, single muon, muon + jets, etc (50% more signal than previous results with specific triggers)
  - Improve algorithms at trigger level
    - CDF is improving the tracking and calorimeter algorithm at trigger level
- Reducing backgrounds
  - MH<135: b-tagging is crucial
    - Secondary Vertex algorithms at CDF
      - 40-50% efficient (tight,loose)
      - 0.5-1% fake rate from light jets
      - S/B improves a factor of 20
      - NN to improve b purity (heavy flavor tagger)
    - Neural Network tagger at D0
      - Used to increase efficiency
      - 50-70% efficient (tight,loose)
      - 0.5-4.5% fake rate



Tools to extract signal

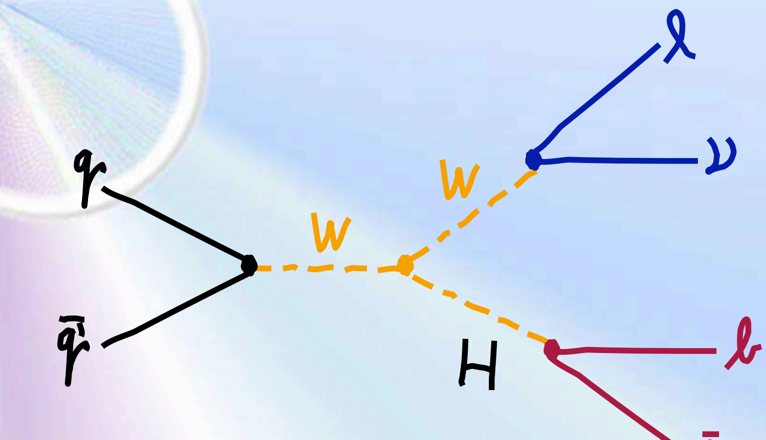
- Dijet resolution
  - Use improved jet energy corrections
  - Use Z->bb to calibrate b-jet response
  - Looking for Z in double tagged events in data
    - Dedicated trigger
      - Required displace tracks
      - Central jets
    - No additional jets above 10 GeV
    - back to back topology



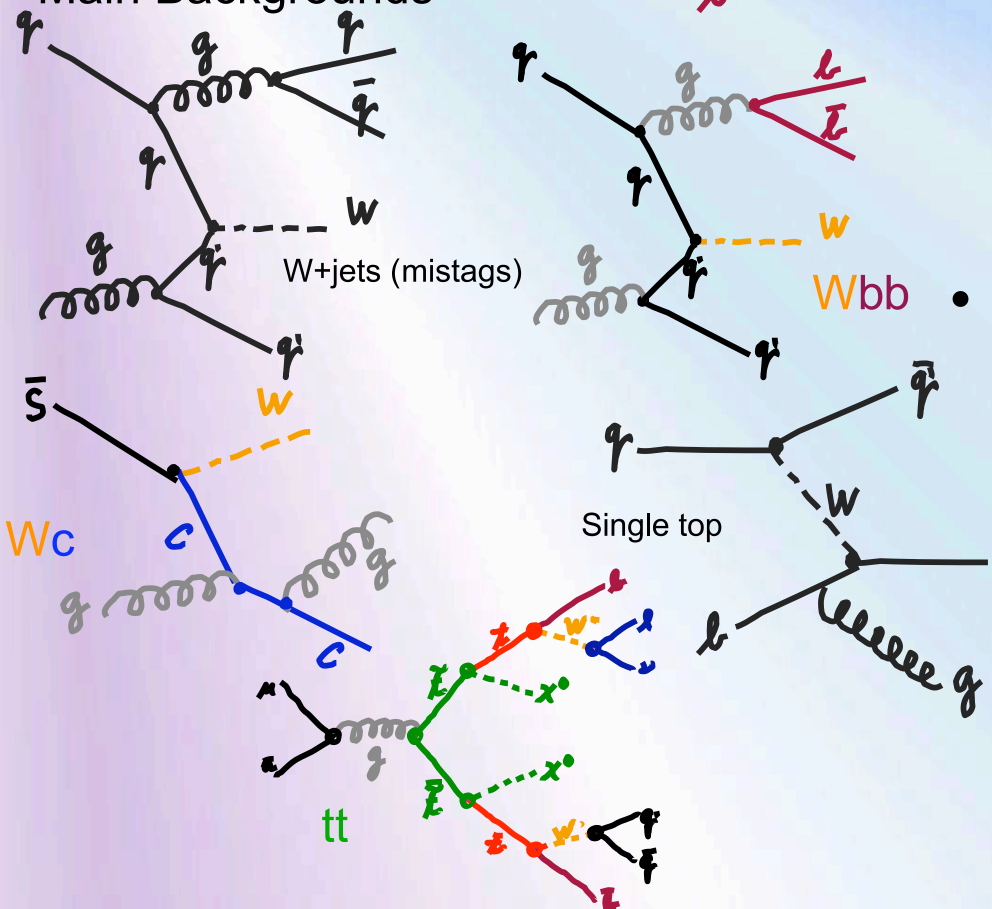
N_{signal} = 5674 ± 448 (stat)

b-jet energy scale factor = 0.974± 0.011(stat) $_{-0.014}^{+0.017}$ (syst)

WH->lν$b\bar{b}$



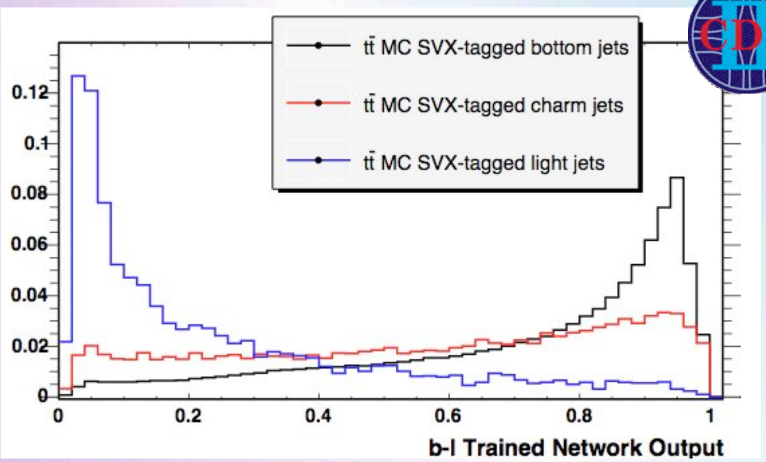
Main Backgrounds



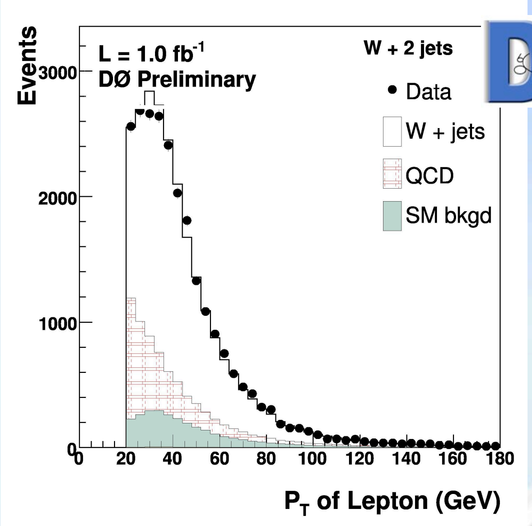
- Signature
  - High Pt isolated lepton
  - Two high transverse energy jets
  - High missing transverse Energy
  - One or two tagged jets
- Backgrounds
  - W+jets (tagged light jet)
  - W+bb/cc
  - Single top and tt
  - Others Dibosons, QCD..

WH->lνb$\bar{b}$: Cut based Analyses

- CDF experiment
  - Isolated lepton e/μ with P_T>20 GeV
  - High Missing E_T
  - Two high jets
  - Tagging requirements
    - 1 b-tagged jet
      - Used NN tagging to further reduce c and light jets
    - 2 b tagged jets
      - No NN requiered
  - Use m_{bb} invariant mass to extract cross section limits



- D0 experiment
  - Isolated lepton e/μ with P_T>20 GeV (full muon coverage)
  - High Missing
  - Two jets E_T
  - Tagging requirements
    - 1 tight b-tagged jet
    - 2 loose b-tagged jet
  - Use m_{bb} invariant mass to extract cross section limits



WH->lνb$\bar{b}$: Cut based Analyses

CDF results:

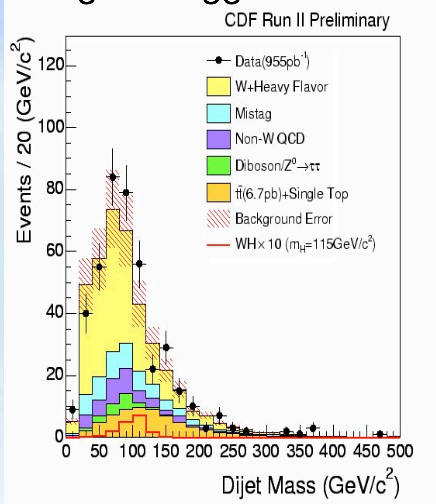
Expect 95% C.L limit (m_H =115 GeV)

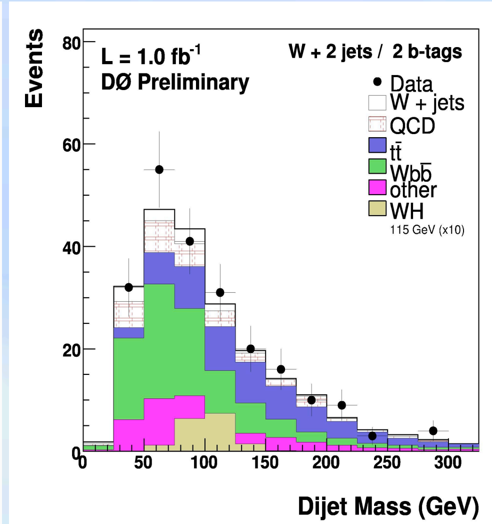
< 2.2 pb (< 17 times over SM)

Observed limits:

< 3.4 pb(< 26 times over SM)

Single b-tagged w/NN





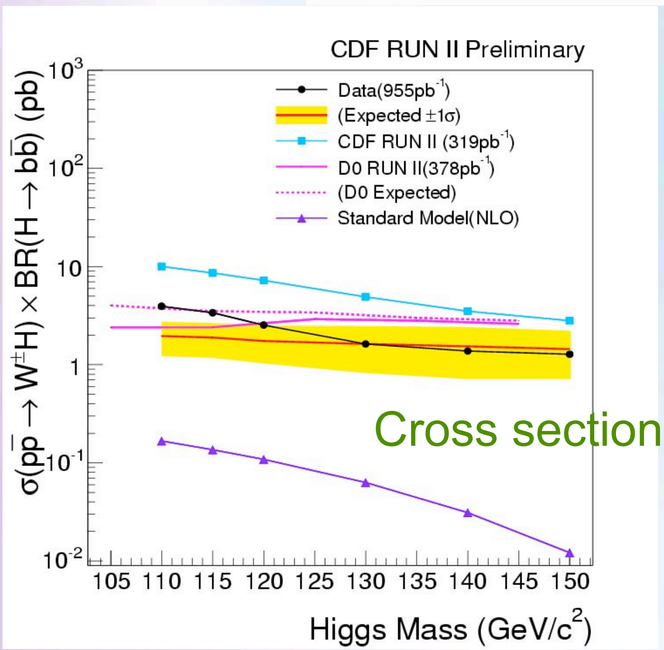
D0 results:

Expect 95% C.L limit (m_H =115 GeV)

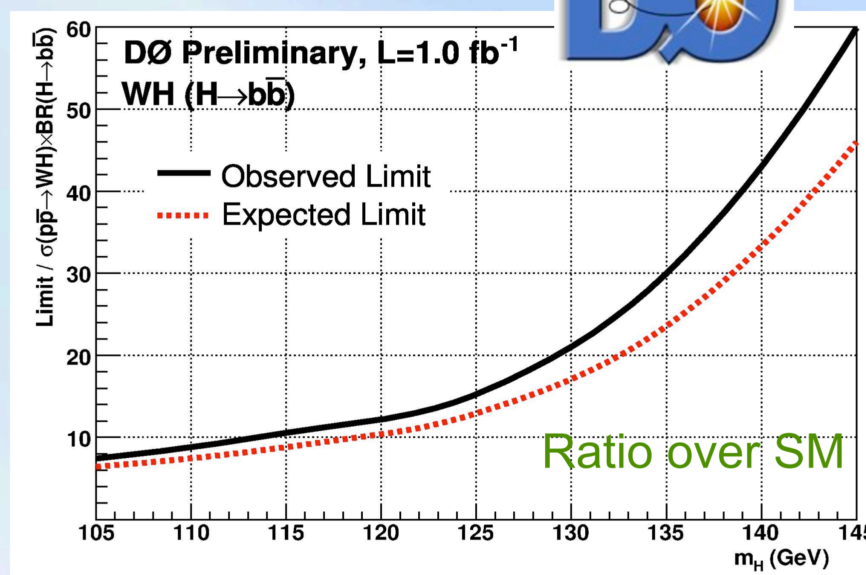
< 1.1 pb(< 9 times over SM)

Observed limits:

< 1.3 pb(< 11 times over SM)

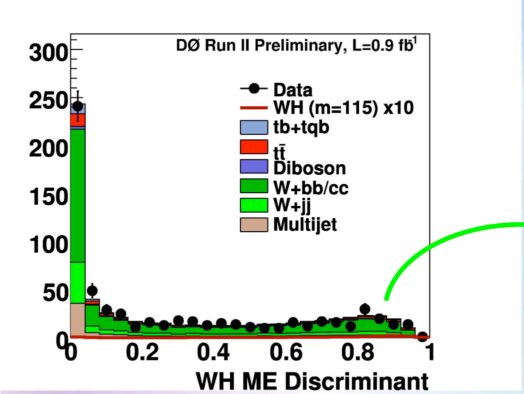


Cross section limit

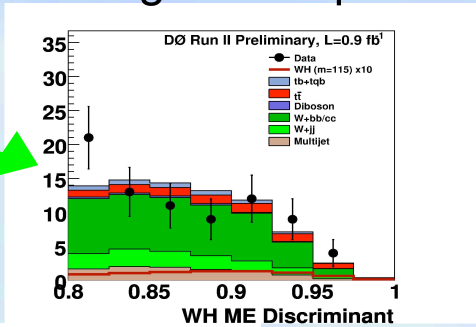


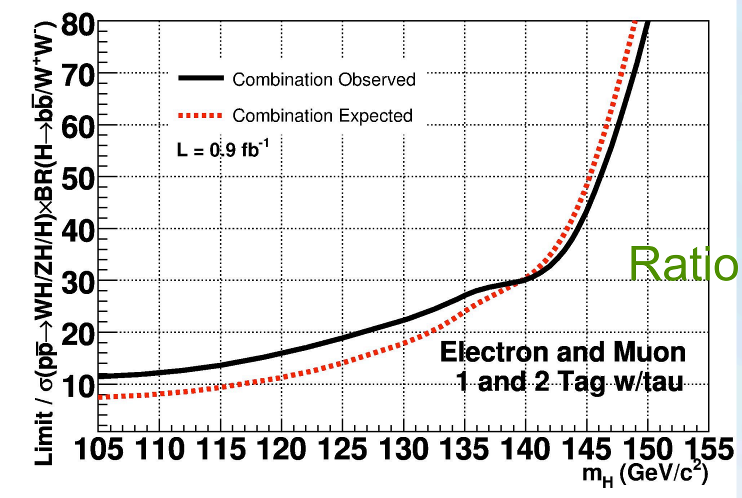
Ratio over SM

WH->l$\nu b\bar{b}$: Matrix Element analysis



1-tag close-up





Ratio over SM

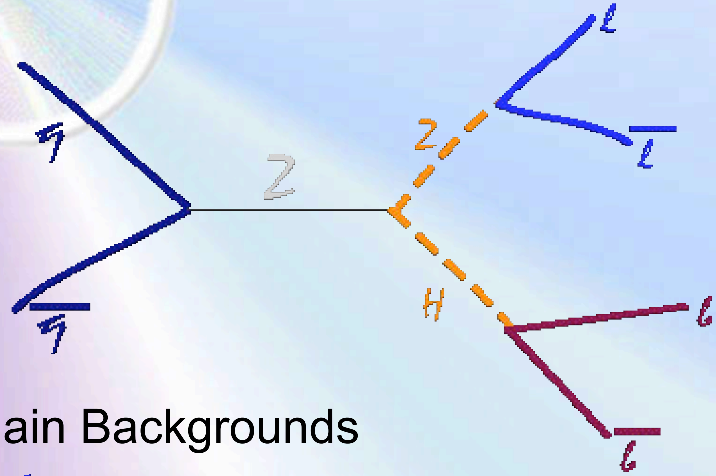
- ME approach to extract signal from background
  - Use LO ME to compute the event probability densities for signal and background
  - Selection criteria based on the single top search (see S. Jabeen's talk)

$$\text{discriminant} = \frac{P_{WH}(\vec{x})}{P_{WH}(\vec{x}) + \sum_i c_i P_{back}(\vec{x})}$$

  - C_i are background fractions, optimized for each Higgs mass considered. Top, dibosons are fixed to their expected values, the others are constraint to their expectations

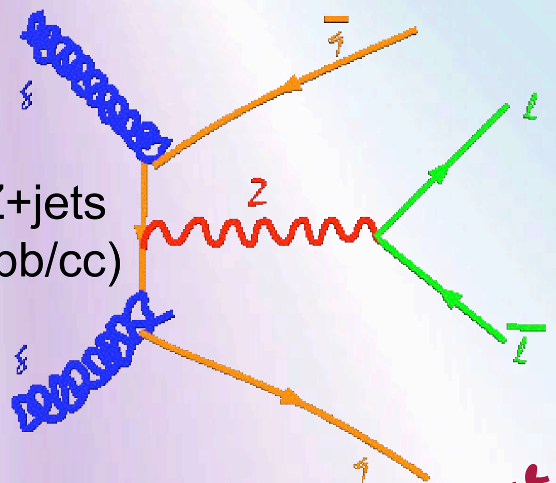
Expected 95 % C.L. upper limit
<1.2 pb (9 times over SM)
Observed limit
< 1.7 pb (12 times over SM)

ZH->$l^+l^-b\bar{b}$

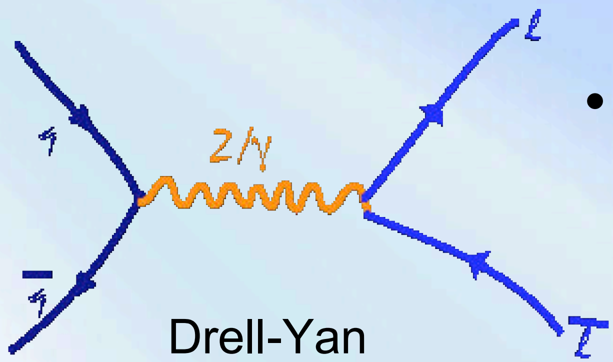


- Signature
  - Two high Pt isolated leptons
  - Two high Et jets
  - At least one b-tagged
- Backgrounds
  - Z+jets, Drell-Yan
  - Z+bb/Z+cc
  - Top
  - Dibosons

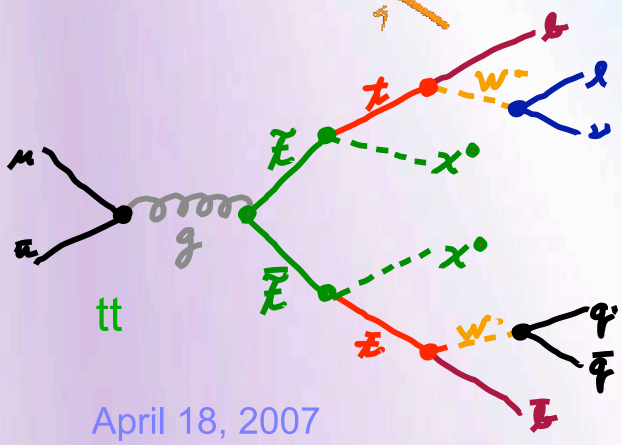
Main Backgrounds



Z+jets (bb/cc)

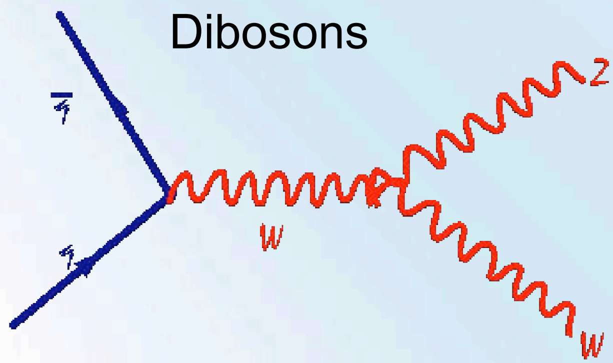


Drell-Yan



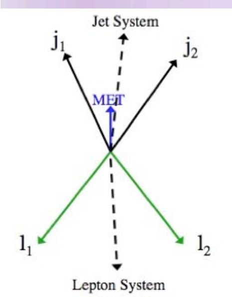
tt

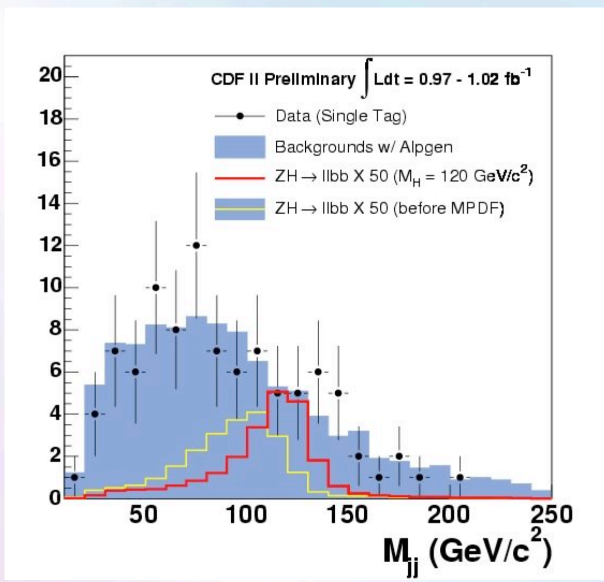
Dibosons



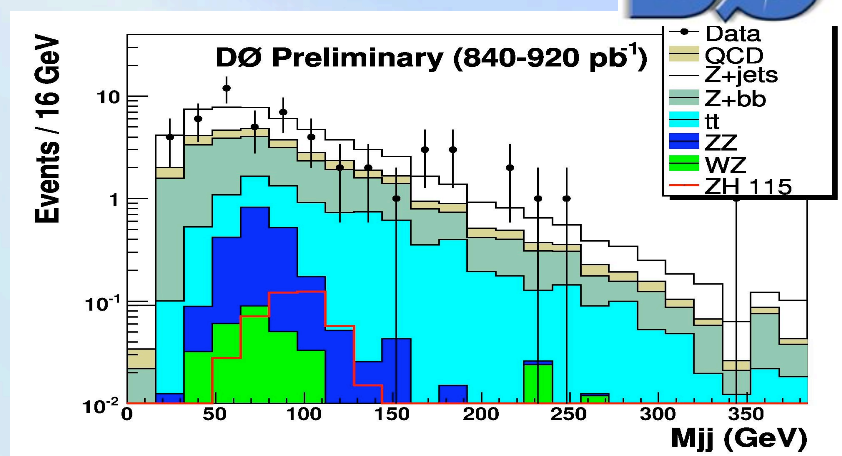
ZH->$l^+l^-b\bar{b}$

- CDF experiment
  - Two high Et jets
  - Two isolated leptons with M_{ll}~M_Z
  - Reduce background
    - One tight b-tagged jet
    - Two loose b-tagged jet
  - Improve dijet mass resolution
    - Corrects jets based on their MET projection
    - Improve dijet mass resolution from 17% to 10%
  - Use 2-D Neural Network discriminant to set limits



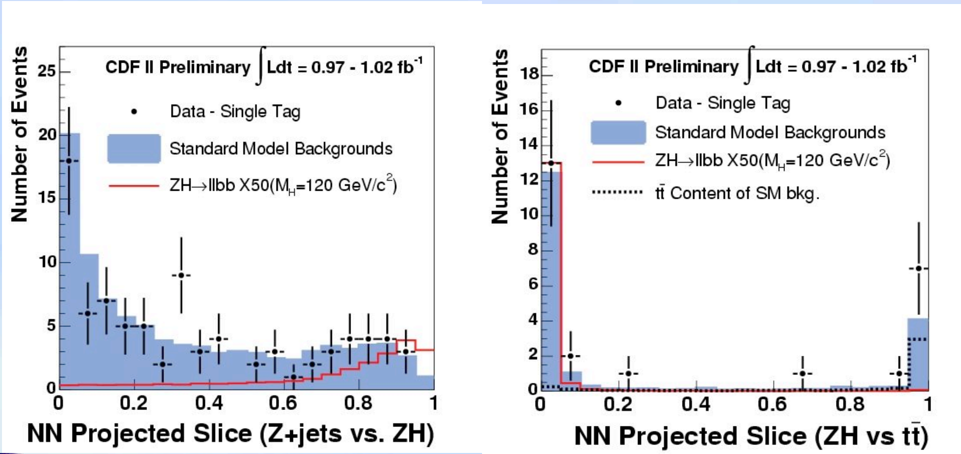


- D0 experiment
  - Two high Et Jets
  - Two isolated leptons wiht M_{ll}~M_Z opposite charge
  - Reduce background
    - Two loose b-tagged jets
  - Use invariant mass distribution, M_{bb}, to set limits

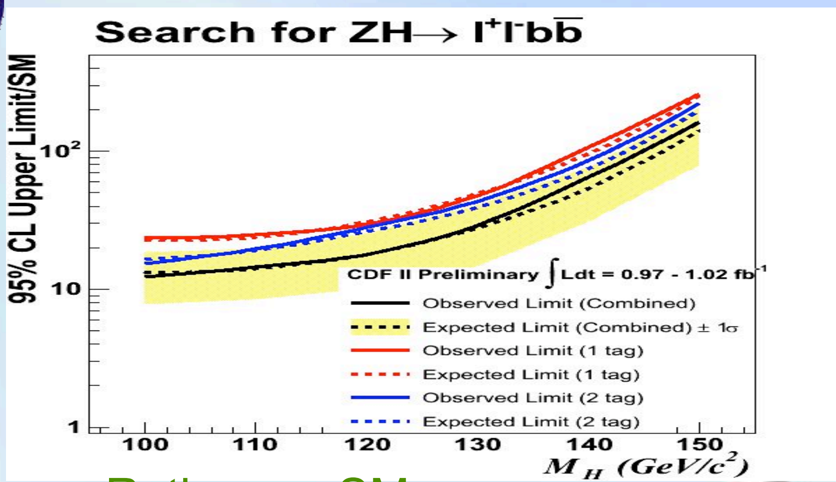


ZH->$l^+l^-b\bar{b}$

- D0 results
  - Expected 95% C.L.(m_H=115 GeV)
    - < 1.81 pb (22 times over SM)
  - Observed limit
    - < 1.88 pb (23 times over SM)

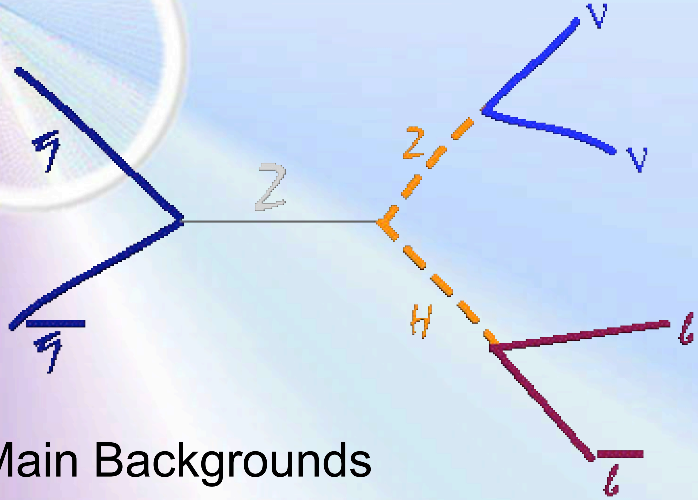


- CDF results
  - Expect 95% C.L. (m_H =115 GeV)
    - < 1.3 pb (16 times over SM)
  - Observed limit
    - <1.3 pb (16 times over SM)



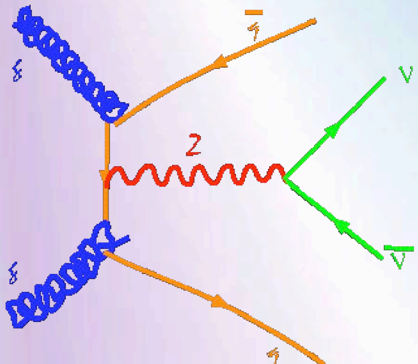
Ratio over SM

ZH->$\nu\nu b\bar{b}$

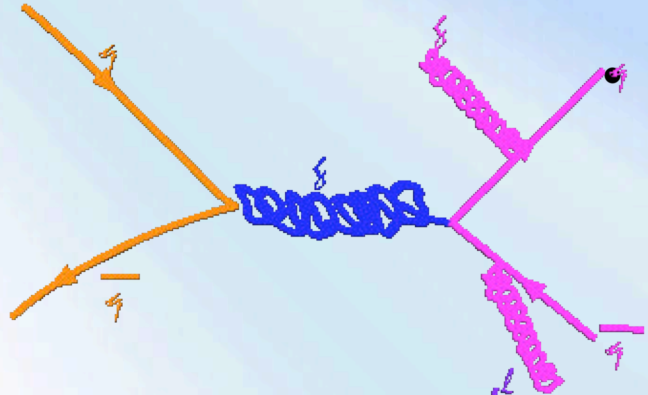


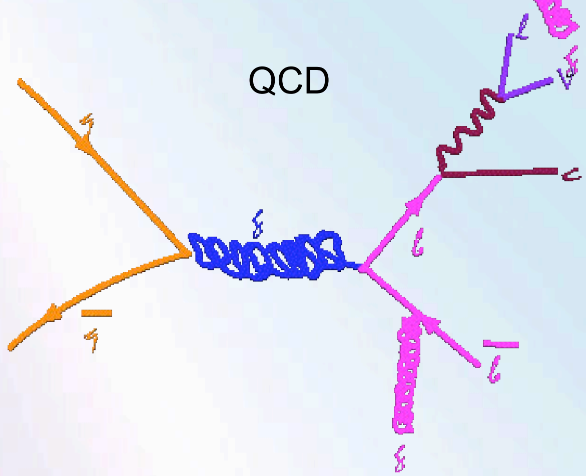
- Signature
  - Two high E_T jets
  - High missing E_T
  - B-tagged jets
  - Jets recoil against MET
- Backgrounds
  - Z+jets, Z+bb/Z+cc
  - W+jets, top, Dibosons
  - QCD: very challenging because of the modeling of the HF and jet misreconstructions
- Advantage
  - WH contributes when lepton is lost

Main Backgrounds

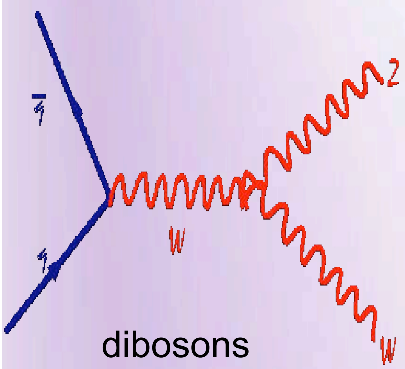


Z+jets
Zbb/Zcc





QCD

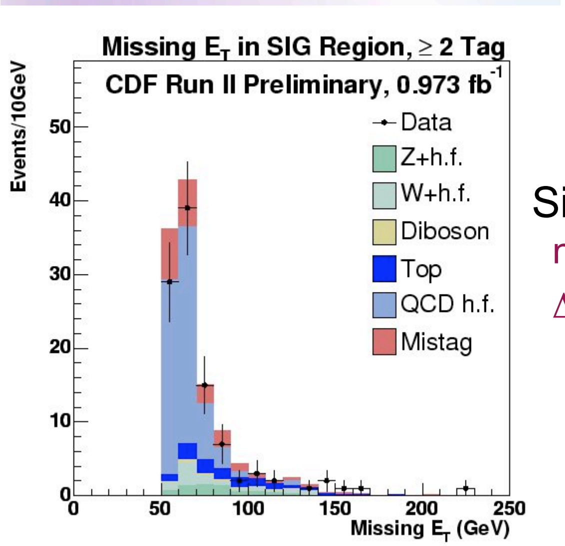


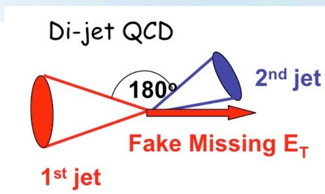
dibosons

ZH -> $\nu\nu b\bar{b}$

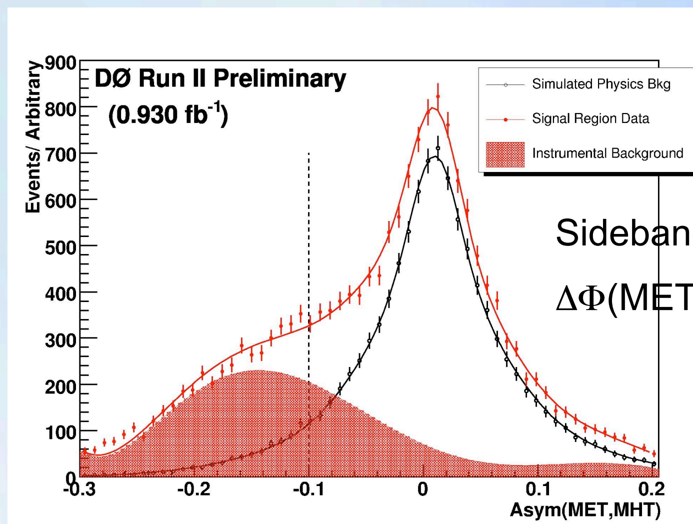
- CDF experiment
  - One very high Jet E_T> 60 (20) GeV, $|\eta|$<1.1(2.4)
  - Missing E_T > 75 GeV
  - Veto isolated leptons
  - Missing E_T not aligned with jets in ϕ
  - Reduce background
    - One b-tagged
    - Two b-tagged
  - Use M_{bb} to extract limits

- D0 experiment
  - 2 Jets, E_T>20 GeV $|\eta|$<1.1(1.4<$|\eta|$<2.5)
  - Missing E_T>50 GeV
  - H_T<240 GeV
  - Veto isolated leptons
  - Primary vertex (>= 3 tracks) $\Delta\Phi(J_1,J_2)<165^o$
  - Other kinematical cuts to reduce instrumental background
  - B-tagging: one loose tag jet and one tight tag jet
  - Use M_{bb} to extract limits in a mass window of 2σ around the mean



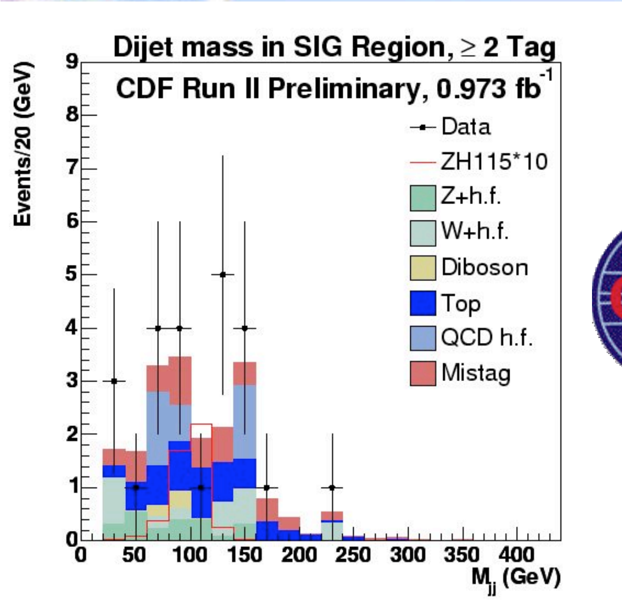


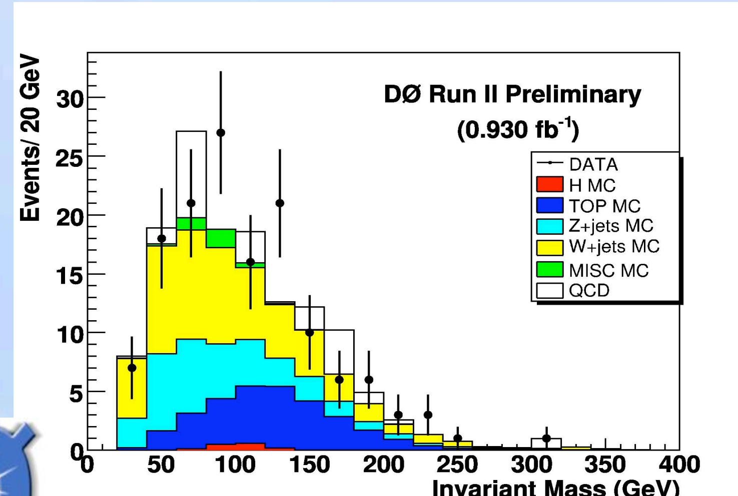
Signal region
no leptons
$\Delta\Phi$(MET, $j_1$orj_2) > 0.4 rad



Sideband region
$\Delta\Phi$(MET,P_t^{negtrk})>π/2

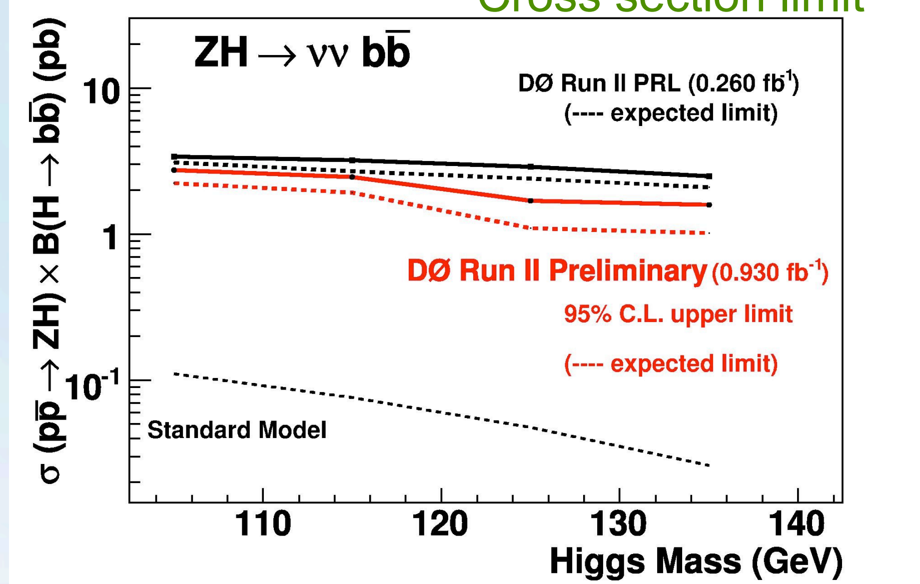
ZH->ννbb



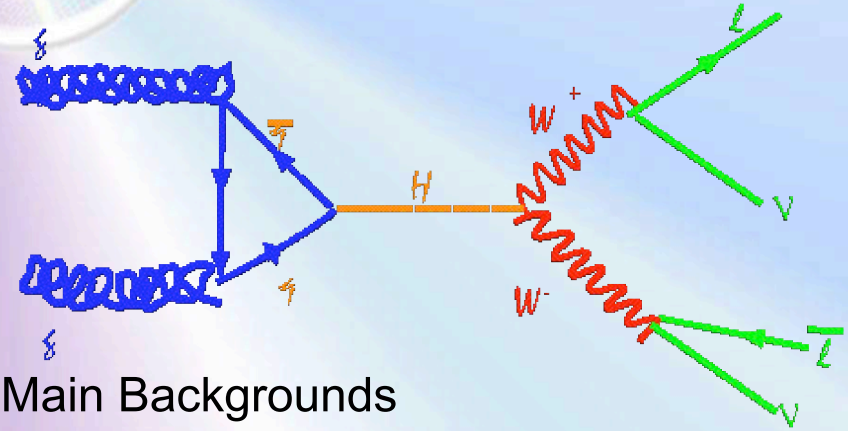


- CDF results (combination of ZH+WH)
  - Expected 95%CL limit (M_H = 115 GeV)
    - 15.4 times over SM for VH
  - Observed
    - 16.0 times over SM for VH
- D0 results(combination of ZH+WH)
  - Expected 95%CL limit (M_H = 115 GeV)
    - 9.6 times over SM for VH
  - Observed
    - 14 times over SM VH

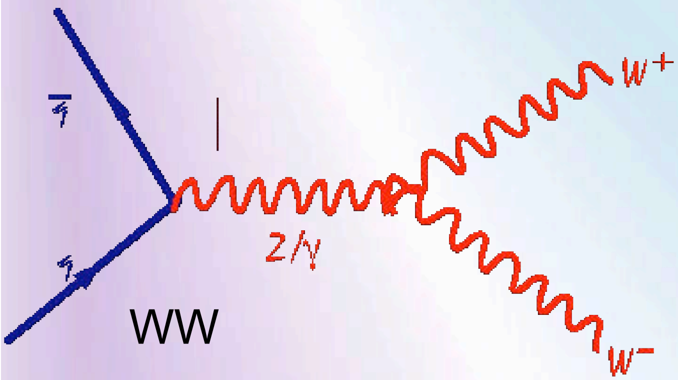
Cross section limit



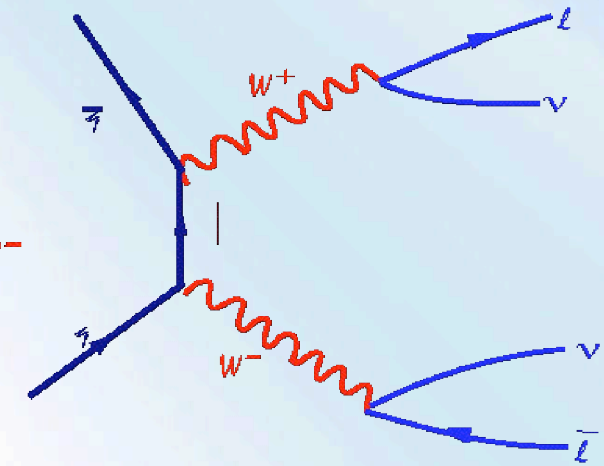
gg-> H -> WW*



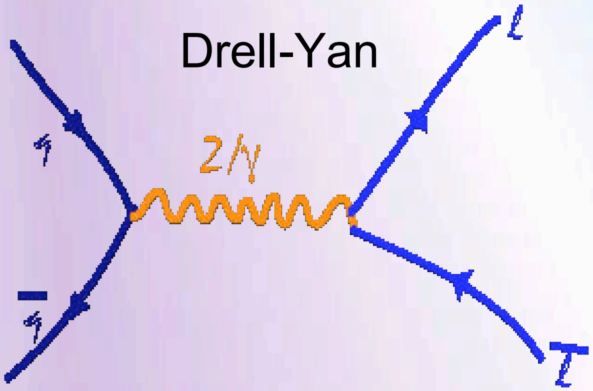
Main Backgrounds



WW



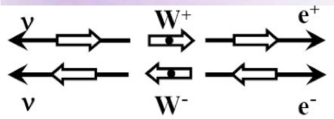
Drell-Yan



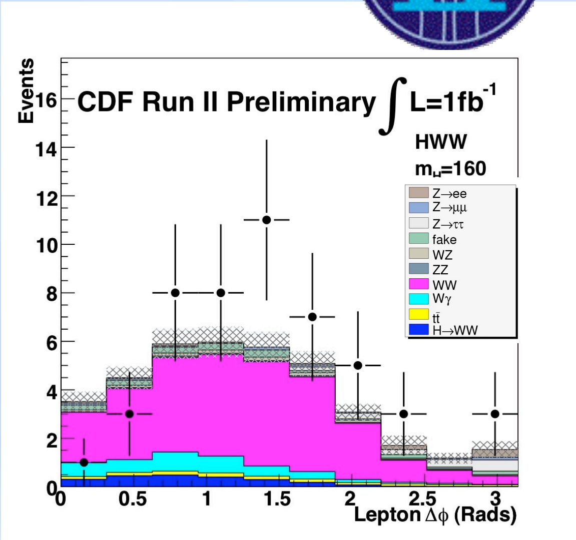
- Signature
  - Two high Pt isolated leptons
  - Large missing Et
- Backgrounds
  - WW
  - Drell-Yan
  - Top
  - WZ,ZZ, Wγ, Zγ

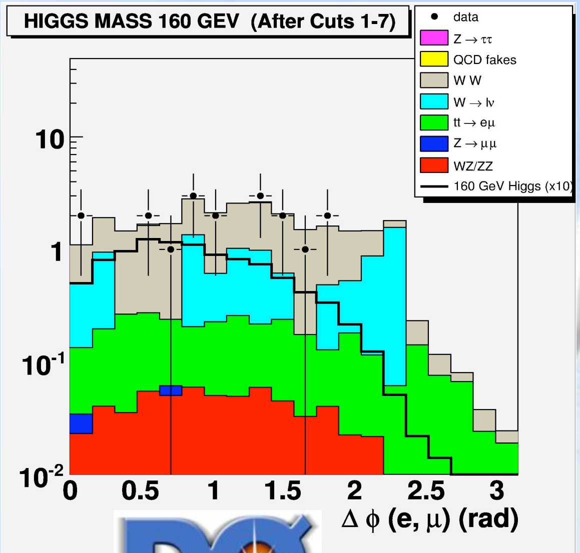
gg->H->WW*

- Both experiments
  - Two high Pt isolated leptons
  - High missing ET (MET)
  - Veto on jets
  - Some kinematical cuts to enhance signal versus backgrounds
  - Strategy:
    - Spin-0 Higgs➔different angular correlation of leptons, prefer to point in the same direction



      - Use of dilepton opening angle $\Delta\Phi_{ll}$ to distinguish against WW background
    - Extract cross section limit from $\Delta\Phi_{ll}$ distribution





D0 results

Expected 95% C.L. Limits

(m_H = 160 GeV)

< 4 times over SM

Observed

< 4 times over SM

CDF results

Expected 95% C.L. Limits

(m_H = 160 GeV)

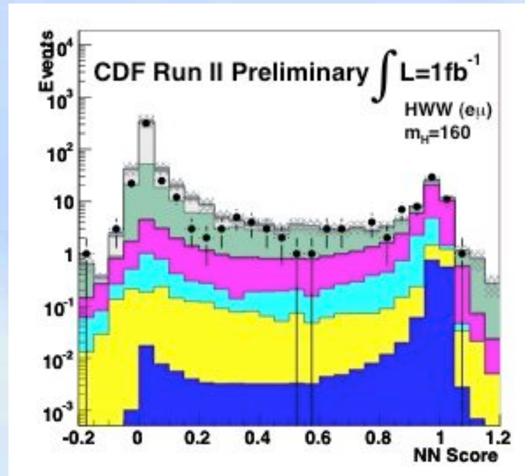
< 6 times over SM

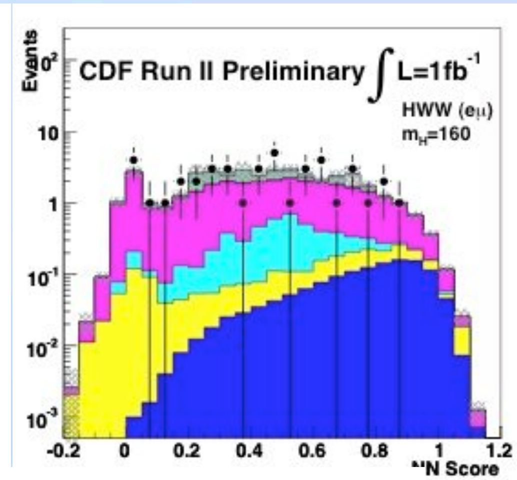
Observed

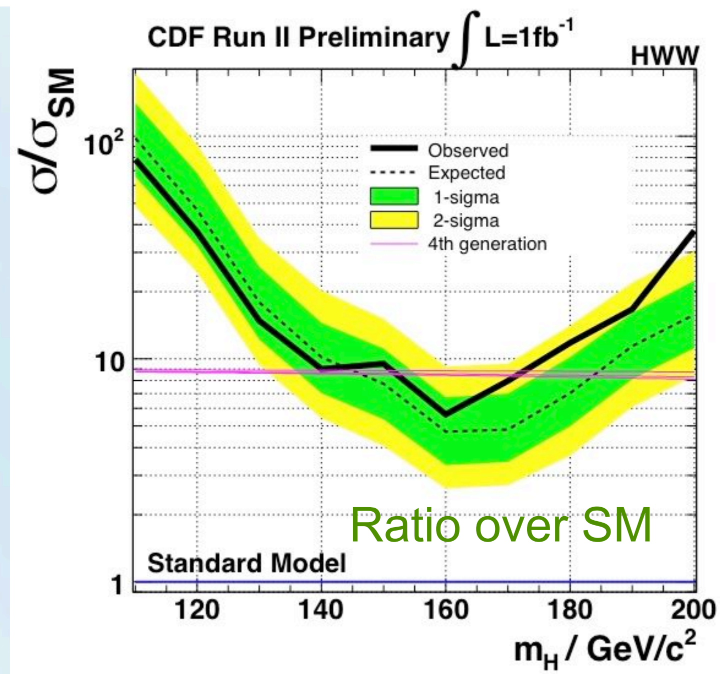
< 9 times over SM

gg->H->WW*

- CDF new analysis
  - Same event selection as cut based analysis
  - Using two NN with 12 input variables, two hidden layers with N+1 and N nodes
    - One to reduce the DY background(trained with M_H =160 GeV and DY samples)
    - Next to separate the WW background(trained with signal M_H = 160 GeV and WW samples)
  - A binned likelihood of the observed NN output is used to extract the cross section limit







CDF results

Expected 95% C.L. Limits (m_H = 160 GeV)

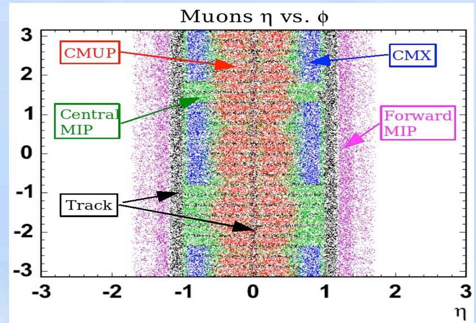
< 5 times over SM

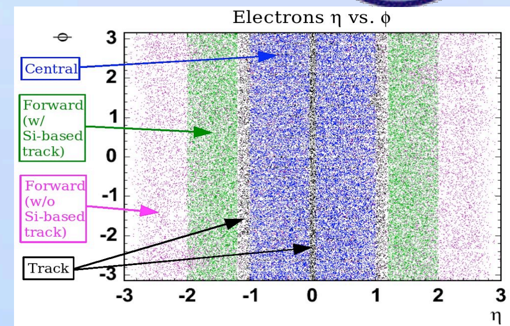
Observed

< 5.6 times over SM

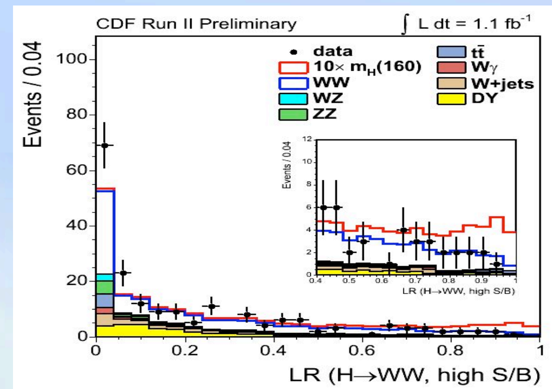
gg->H->WW*

- CDF improvements
  - Improve lepton acceptances
    - Use of WZ->lνll analysis, lead from evidence to discovery with 5.9 sigma of WZ
    - H->WW use many of this categories ➔ expected sensitivity 2.5 -> 4 sigmas





  - Matrix element approach to differentiate signal from background.
    - Likelihood ratio $\text{discriminant} = \dfrac{P_{WH}(\vec{x})}{P_{WH}(\vec{x}) + \sum_i c_i P_{back}(\vec{x})}$



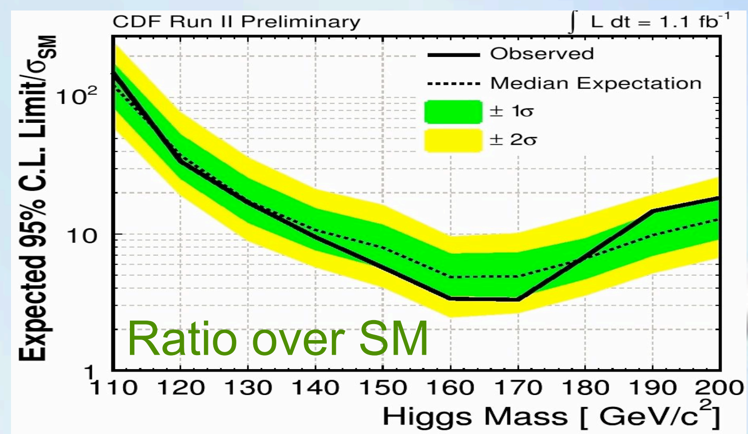
CDF results

Expected 95% C.L. Limits (m_H = 160 GeV)

< 5 times over SM

Observed

< 3.5 times over SM

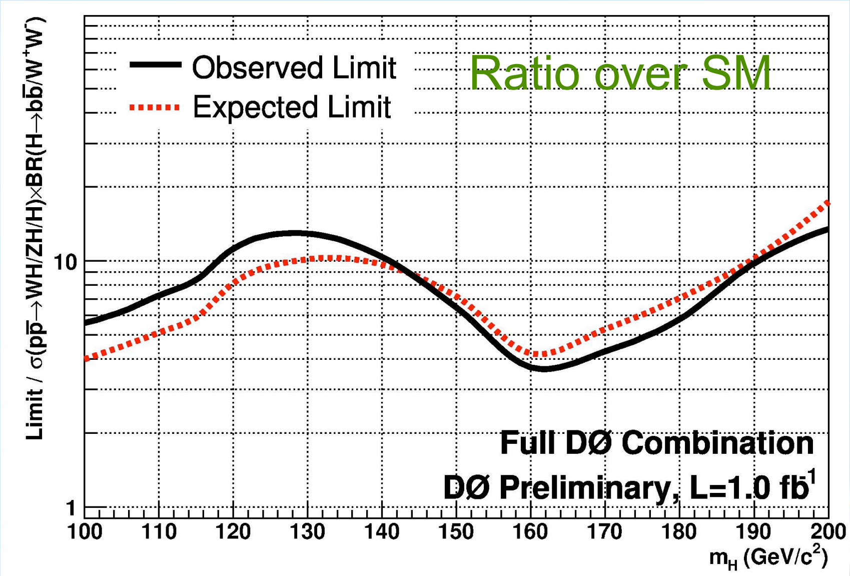


Combination

- D0 has set cross section upper limits Higgs production for masses from 100 to 200 GeV, combining all different channels:
  - WH (M_H = 100-150 GeV
  - ZH (M_H = 100-150 GeV)

  M_{bb} use to set limits
  - H->WW(M_H = 120 -200 GeV)

  $\Delta\Phi$(l,l) use to set limits
- The results are combined using the CLs method with "LR test statistics"



D0 combined results

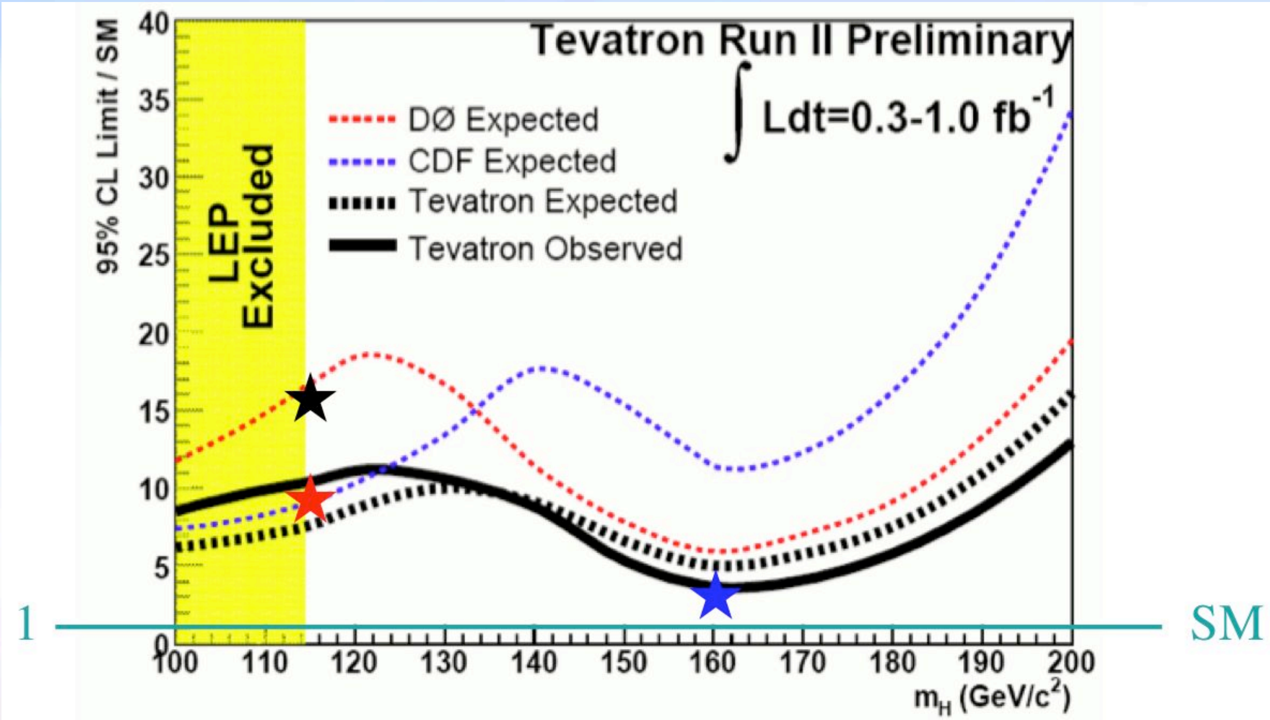
Expected limit

5.9(4.7) over SM M_H = 115 GeV(160 GeV)

Observed limit

8.4(3.7) over SM M_H = 115 GeV (160 GeV)

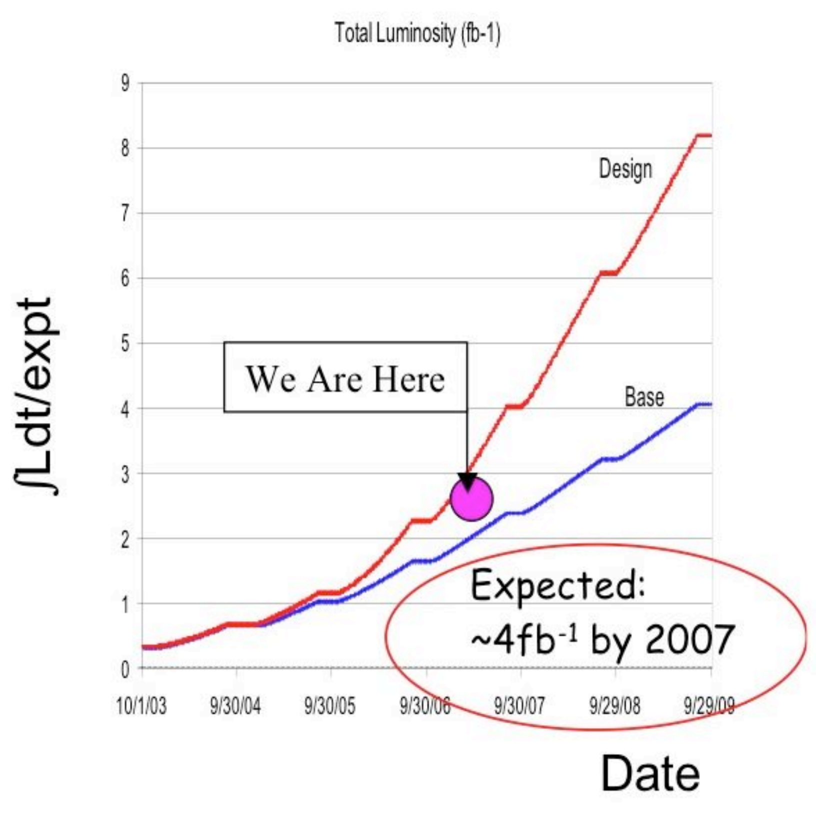
Combinations



- The above limits do not include:
  - New CDF ZH->llbb results ★ (factor of 1.3 improvement from last results)
  - New CDF H->WW results ★ (factor of 1.8 improvements from last results)
  - New D0 WH results ★(factor of 5 improvements from last results)
  - The latest D0 combination just shown
- First Tevatron combined limit released last summer
- Expect significant improvements with these new measurements in and with all 1fb^{-1} results finalized

Conclusions

- Tevatron and CDF/D0 are performing very well
  - Already two times the data shown today
- New results are scaling much better than just the luminosity factor
  - Individual cross section limits only of one order of magnitude above SM
  - Some new results already as good as Summer 2006 Tevatron combination
- Work intensively on improvements to the analysis:
  - Increase lepton acceptance
  - Improve jet resolution
  - Improve b-tagging
  - Used advance analysis techniques (Matrix Element, NN, Boosted Decision Trees, etc)
    - ZH improve factor ~ 1.3 from refine analyses
    - WH improve factor ~1.8 from luminosity and refine analysis
    - H->WW improve a factor ~5 from luminosity and refine analysis



More to come soon

STAY TUNED

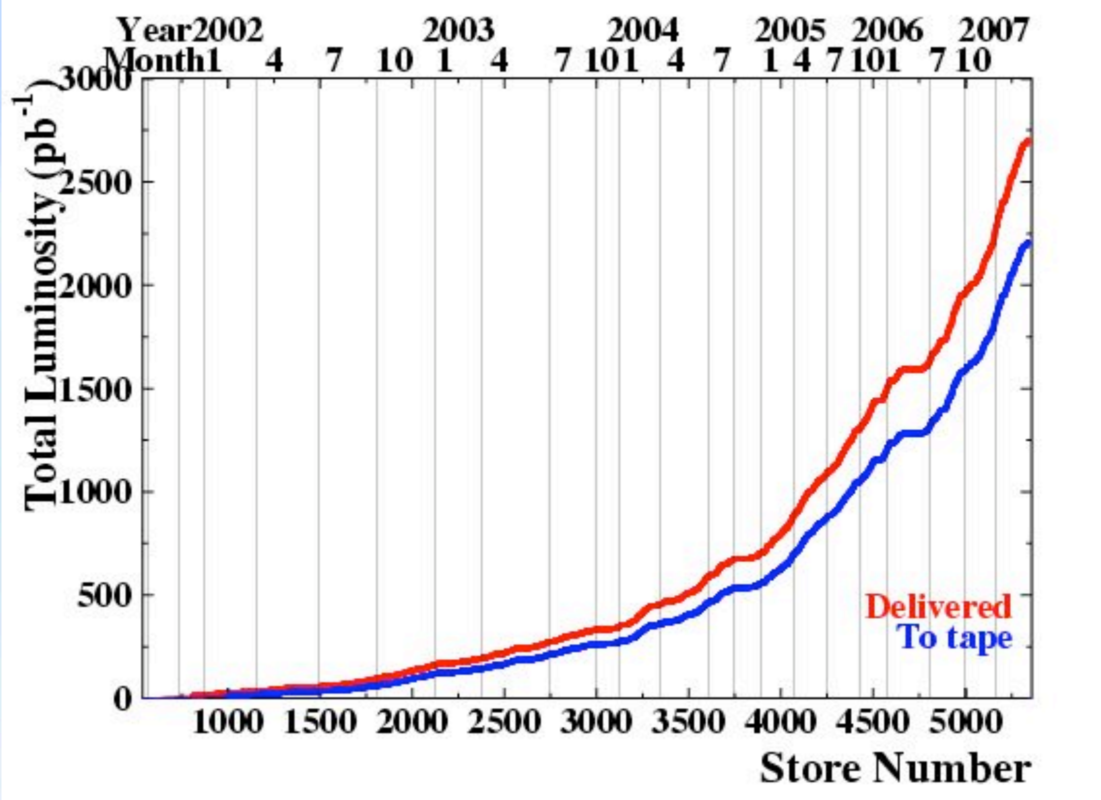
Summary

Analysis	CDF limit ($1fb^{-1}$) factor above SM observed (expected)	D0 limit ($1fb^{-1}$) factor above SM observed (expected)
Z/WH→MET+bb @ 115 Technique: M_{jj}	16 (15)	14 (9.6)
WH→lνbb @ 115 Technique: M_{jj} Technique: ME	 26 (17) -	 11 (8.8) 12 (9.5)
ZH→llbb @ 115 Technique: M_{jj} Technique: NN2D	 - 16 (16)	 23 (22) -
H→WW→lνlν @ 160 Technique: $\Delta\phi$(l,l) Technique: ME	 9.2 (6.0) 3.4 (4.8)	 3.7 (4.2) -
$\Phi \to \tau\tau$ @ 160 μ<0, no mixing	 tanβ < 69 (47)	 tanβ < 44 (54)

Backup Slides

Backup slide: Luminosiy

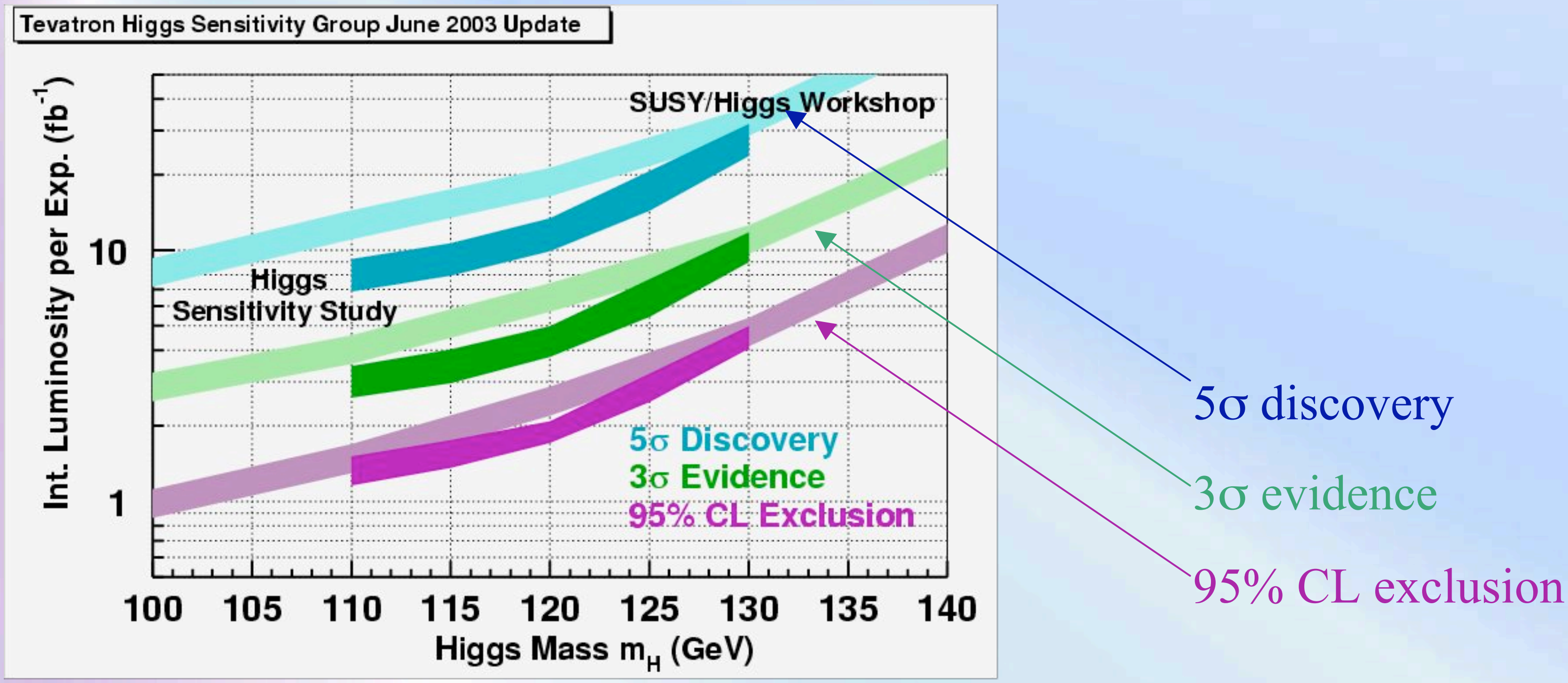
- Run II sqrt s = 1.96 TeV
- Peak luminosity record:
  - 2.8 X1032 cm-2 s-1
- Interated luminosity
  - Weekly record:
    - 40 pb-1 /week/expt
  - Total delivered: ~2.5 fb-1 /expt.
  - Total recorded:~ 2. Fb -1 /expt.



Expect 4 fb-1 by the end of this year

Higgs Sensitivity
(DØ: $\nu\nu bb$+ $llbb$, CDF: $l\nu bb$; CLS comb)

Combined DØ/CDF Result

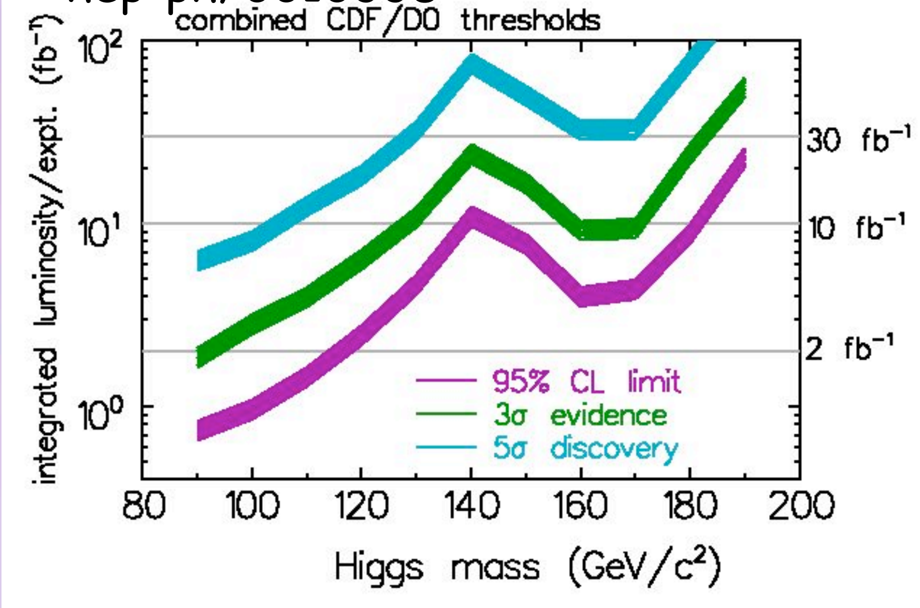


shown sensitivity at M_H = 115 GeV with 1.5 fb^{-1} per experiment

- D0 combination is about a factor 7 above the expectation for 1.5 fb^{-1} BUT:
  - Only lum. factor taken into account
  - Still plenty of room for improvements
  - CDF is missing in this combination

Sensitivity Projections from 2000 and 2003

hep-ph/0010338



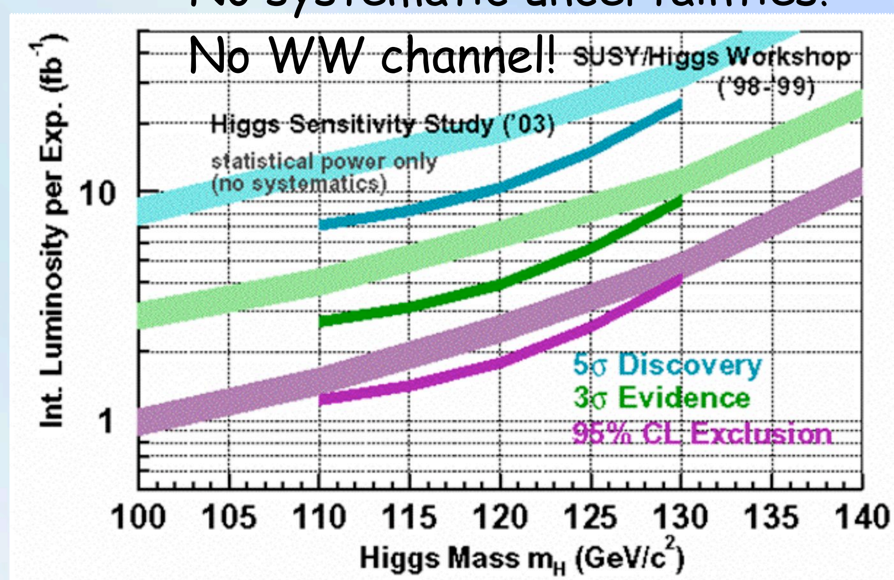
2003: Realistic detector models
Data-based backgrounds @
Run II energies

Analysis upgrades assumed
Acceptance upgrades
Sophisticated s/b separation

No systematic uncertainties!
No WW channel!

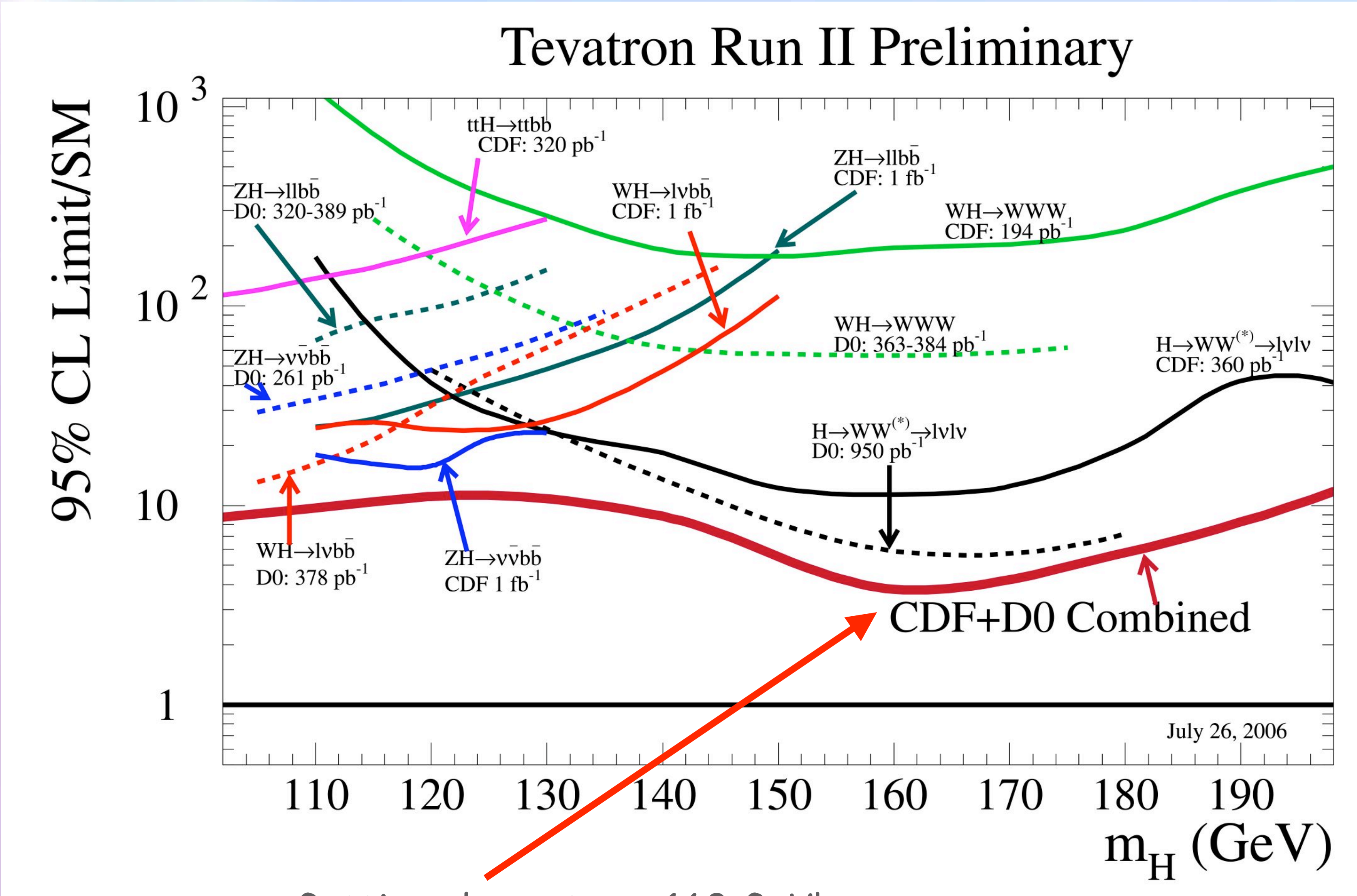
1999: Run I extrapolations
Attempt at syst. errors:
scale with 1/sqrt(L)

Includes WW channel
MC models of Run II detector
performance



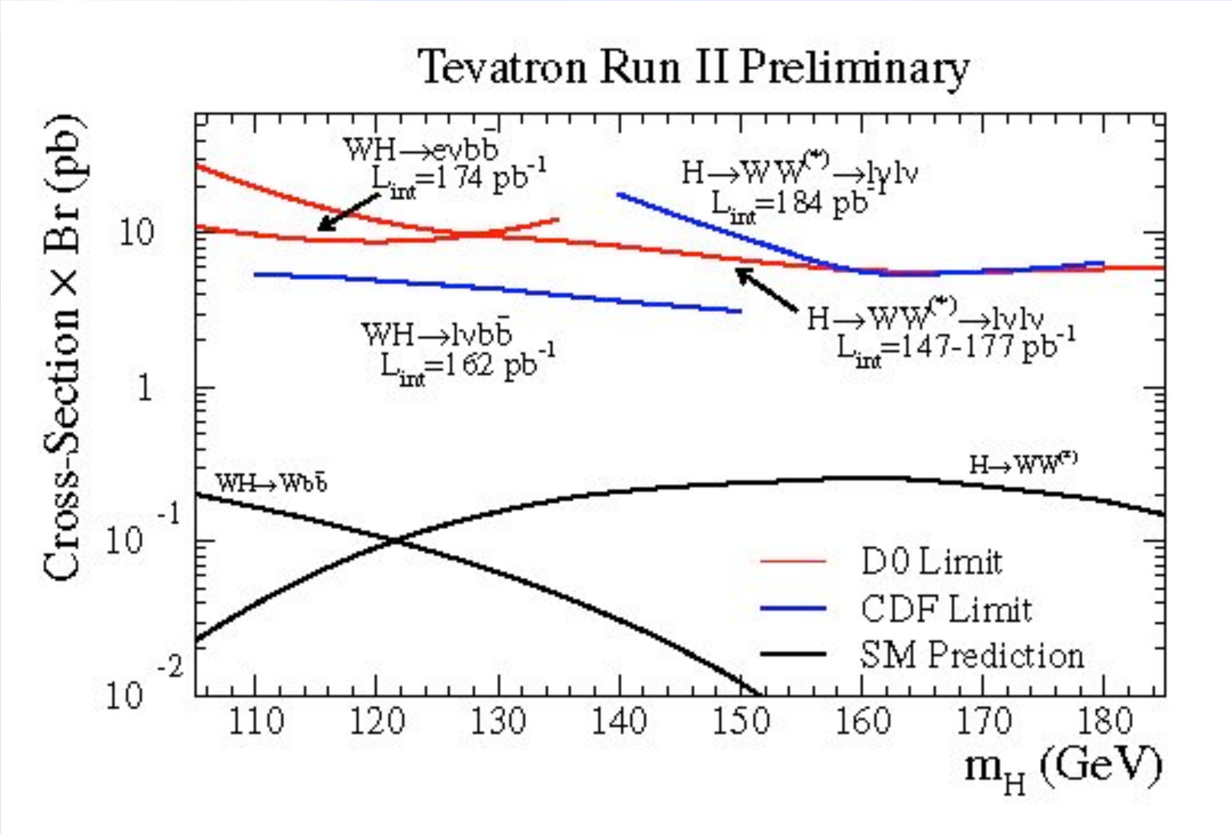
Fermilab-Pub-03/320-E

The State of the Individual Channels as of ICHEP 2006



Getting close at m_H=160 GeV!

Just a Short While ago, It looked like THIS



La Thuile/Moriond 2005

In just over a year, we analyzed 6× the data, optimized the analyses, and combined them together to close in on the SM.

Searches gaining staff and momentum!

The Old To-Do List, of October 2005

Improvement	WH→lνbb	ZH→ννbb	ZH→llbb
Mass resolution	**1.7**	**1.7**	**1.7**
Continuous b-tag (NN)	1.5	1.5	1.5
Forward b-tag	1.1	1.1	1.1
Forward leptons	1.3	1.0	1.6
Track-only leptons	1.4	1.0	1.6
NN Selection	**1.75**	**1.75**	**1.0**
WH signal in ZH	**1.0**	**2.7**	**1.0**
Product of above	8.9	13.3	7.2
CDF+DØ combination	2.0	2.0	2.0
All combined	17.8	26.6	14.4

SM Channels only

Doesn't specify what WW people should do.

We thought they were pretty optimal already.

We are learning there is much more to be gained in WW

Much has been learned in the last year.

Lots left to learn, and do.

Accomplishments and Ideas – Mass Resolution

Improvement	WH→lνbb	ZH→ννbb	ZH→llbb
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All combined	17.8	26.6	14.4

Many of these we have tools for, but need to convince ourselves in data that they perform as promised.

Watch out for multiple collision effects..

MET resolution too..

Current Status:

- Many tools available:
  - NN Jet tools
  - Hyperball (kind of like an NN)
  - Track-Cluster Association
  - B-specific Corrections
  - Wider Jet Cones (llbb already uses these)
  - Selection nets implicitly optimize m_{jj} resolution if they include such things as MET and EM fraction and other things a NN needs (llbb).
  - Double-tagged events have better m_{jj} resolution than single-tagged events (less combinatorics, less semileptonic decay)

A Continuous Job: NN Selection

Improvement	WH→lνbb	ZH→ννbb	ZH→llbb
Mass resolution	**1.7**	**1.7**	**1.7**
Continuous b-tag (NN)	1.5	1.5	1.5
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llbb Channel already has a 2D NN!

WH→lvbb tried a NN analysis already. Claim: 1.75 factor in HSWG note; Run I NN gets 1.2 factor in s/sqrt(b)).

Single top NN's have shown tremendous improvements in sensitivity over simple variables like M_{lvb} and H_T.

We learn as we go: Matrix Element Techniques perform very well and give results not 100% correlated with NN's.

But – some measured quantities are not input to the Matrix Element, like NN b-tags.

Many kinds of backgrounds lack convincing matrix elements

Non-W